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Title: Nonlinear Signal Processing Schemes for Robust Target Detection and Automatic Clutter Rejection in Radar

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I. INTRODUCTION

In earlier work, a technique called "Split-Spectrum Processing" (SSP) was developed to achieve frequency diversity in one-dimensional (A-scan) ultrasonic applications. In SSP, a wideband signal is transmitted and the received signal spectrum is partitioned into different frequency bands using spectral windows to obtain a set of decorrelated signals as shown in Fig. 1. Once the decorrelation of grain echoes has been achieved through SSP, noise suppression algorithms can be applied to the resulting data to enhance the target signal. Therefore, SSP eliminates the need for complex modulation techniques or multiple transmitters to achieve frequency diverse signals at the receiver. In addition, the SSP technique allows a different set of decorrelated data to be obtained conveniently by re-partitioning the existing raw data using a new set of window parameters, thus eliminating the need to recollect data. Because of its effectiveness and versatility, the SSP technique has been widely utilized both in nondestructive testing and imaging applications, and in this work its application to radar has been examined.

It should be noted that decorrelation of clutter echoes can also be achieved by means of distributed array of receivers or transmitters. Therefore, target enhancement can be achieved by combining spatially decorrelated signals. Although this approach is also effective in decorrelating clutter and easier to implement in real-time, it is not as versatile as the SSP technique since it requires a more complicated and costly system.

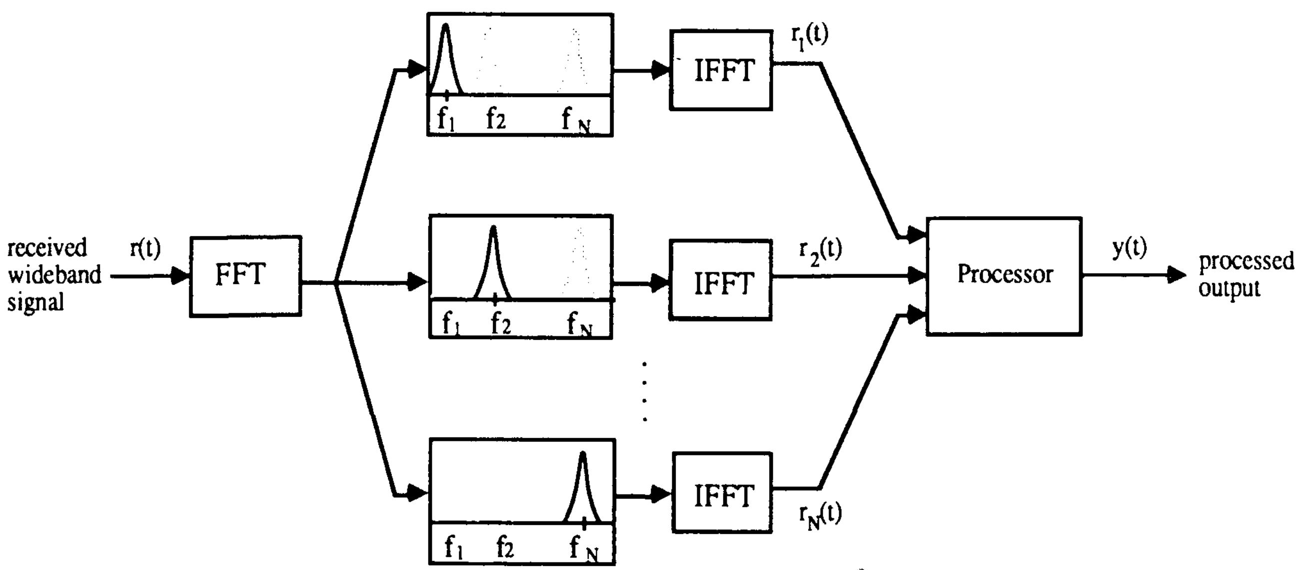

Figure 1. Block diagram representation of split-spectrum processing

SIGNAL PROCESSING ALGORITHMS

The target signal enhancement algorithms based on spectral techniques (e.g. SSP) are generally designed to detect and emphasize the differences in the behavior of clutter and target echoes to shifts in the transmitted frequency. When the target of interest is much larger than the average size of the clutter causing reflectors, varying the frequency will have a relatively minor affect on the target echo. However, in a resolution cell containing a large number of reflectors, even a small shift in the frequency can alter the resultant clutter interference pattern significantly. Although a small shift in the frequency contents of the transmitted signal may have only a minor effect on an individual component of clutter, which may be represented as an independent vector with frequency dependent phase and magnitude, when a large number of such unresolved echoes combine, the effect on the resultant clutter is often significant. The sensitivity of clutter to frequency shift is determined by many complex factors such as scattering, clutter density and cross section, multipath, attenuation, etc. Therefore, in order to improve the signal-to-noise ratio (SNR) it is necessary to develop algorithms which can effectively distinguish between clutter and target echoes.

If the wideband input to the N-window SSP system shown in Fig. 1 has M data points, then the output will consist of N individual signals each having M data points which correspond to different spectral regions (i.e. unique center frequencies) with fixed bandwidths. Therefore, the output of the 1-D SSP results in an NxM matrix whose columns consist of decorrelated data corresponding to fixed time instants but different frequency bands. The noise suppression algorithms recombine or process the data in each column to obtain an enhanced target signal. Two major nonlinear algorithms have been developed, which produce significant clutter suppression namely, minimization and polarity thresholding.

2.1 Minimization Algorithm

The minimization algorithm is based on the principle that at time instants where the target signal is present the corresponding SSP data set will show only minor variation in magnitude. However, at time instants where only clutter is present there will be significant variation in the magnitude of clutter corresponding to different frequency bands. Therefore, by selecting the minimum magnitude at each time instant the target signal can be enhanced since clutter suppression will be significantly greater. The minimization process can be expressed as follows

$$y_{MIN}(t_k) = \mathrm{MIN}\left[\, |r_i(t_k)| \,;\ i=1, 2, \ldots N \text{ and } k=1, 2, \ldots M\right] \qquad (1)$$

where N is the number of window outputs having M data points each.

2.2 *Polarity Thresholding Algorithm*

The polarity thresholding algorithm is based on the principle that at time instants where the target signal is present the corresponding SSP data set will not exhibit any polarity reversal since the target signal will be more dominant than clutter (i.e. all the elements of the corresponding column will have the same polarity). However, if the data set contains only clutter, which is assumed to be zero-mean at the detector input, then it is likely that the data will exhibit polarity reversal. Therefore, by setting the amplitude of the processed signal to zero at time instants where polarity reversal occurs while maintaining the original value of the unprocessed wideband signal when the data has identical polarity, the clutter level can be reduced significantly. Therefore, the PT output can be expressed as

$$y_{PT}(t_k) = \begin{cases} r(t_k) & \text{if } r_i(t_k) > 0 \text{ or } r_i(t_k) < 0 \text{ for all } i = 1,2, \ldots, N \\ 0 & \text{otherwise} \end{cases} \qquad (2$$

where t_k are discrete time instants with k=1,2, ... , M. Alternatively, the non-zero portion of the PT data can be obtained from the output of any other SSP algorithm, such as minimization. In particular, linear averaging and mean/standard deviation algorithms, which individually are not very effective in reducing grain noise, may be treated as the input to the PT algorithm. These algorithms are briefly described here:

2.3 *Linear Averaging Algorithm*

The output is obtained by linearly averaging the data in each column as follows:

$$y_{LA}(t_k) = \frac{1}{N} \sum_{i=1}^{N} r_i(t_k) \qquad (3)$$

where the sum term is identical to the original wideband signal $r(t_k)$ for rectangular and non-overlapped windows. However, this is not the case in experimental processing where, in general, overlapped Gaussian windows are used whose outputs are normalized to unity amplitude and the low-power windows are eliminated prior to processing. Therefore, LA output is useful in determining the subtle effects of SSP, which are often ignored in the theoretical derivations. However, experimental results have shown that LA does not provide noticeable improvement in SSP applications.

2.4 *Mean/Standard Deviation Algorithm*

This algorithm, which was originally developed for ultrasonic testing and later extended to imaging, determines the ratio between the mean and the standard deviation of the data in each column .

$$Y_{MSD}(t_k) = \frac{< r_i(t_k) >}{\sqrt{< r_i^2(t_k)> - < r_i(t_k) >^2}}$$

where

$$<r_i(t_k)> = \frac{1}{N}\sum_{i=1}^{N} r_i(t_k) \quad \text{and} \quad <r_i^2(t_k) > = \frac{1}{N}\sum_{i=1}^{N} r_i^2(t_k)$$

with $k = 1, 2, \ldots, M$.

Both theoretical and experimental results have shown that only a minor improvement can be achieved using MSD.

It should also be noted that the algorithms can be modified by imposing different set of criteria on output selection, i.e., for minimization the second or third smallest values can be selected, and in PT the threshold can be set such that one or more polarity reversals can be tolerated, or the data may be weighted based on the number of polarity reversal, etc. Such minor modifications may reduce probability of error under certain conditions and enhance performance.

In radar, the interference due to clutter or jamming can severely deteriorate the quality of the received signal to the point of concealing the target. The main objective of this research effort has been to improve radar detection in high density clutter or jamming environments, by using nonlinear signal processing algorithms in conjunction with robust frequency diversity techniques . A major consideration in the design of signal processing techniques for radar detection systems has been the capability of discriminating between various types of targets and interference. Several nonlinear signal processing algorithms have been introduced and investigated for target detection in clutter. The investigation involved the theoretical analysis and numerical/ experimental verification of two major classes of nonlinear signal processing techniques, namely split-spectrum processing and order statistic filtering. These results demonstrate the superior performance of the novel algorithms introduced and indicate their feasibility in radar detection, thus warranting further investigation and examination of hardware implementation.

During the initial phase of the project dealing with split-spectrum processing (SSP), computer simulations and actual radar images have been used to evaluate the performance of the minimization and polarity thresholding (PT) algorithms. In addition, these results were shown to be consistent with

our theoretical analysis. Various clutter models were simulated to ascertain the dependence of algorithm performance on clutter statistics. Using experimental land radar data, it has been demonstrated that significant image enhancement can be obtained by effective clutter suppression. Thus, demonstrating the feasibility of the nonlinear split-spectrum processing algorithms for detecting actual radar targets in clutter. New algorithms have been developed which combine and/or modify the properties of the two algorithms to further enhance their performances. These algorithms are designed to have robust and/or adaptive capabilities with respect to clutter. Such new algorithms may prove to be more effective in detecting targets in particular clutter environments and allow the optimization of the nonlinear algorithms under specific clutter and target conditions.

In the order statistic (OS) filter investigation, a sort function has been introduced, which provides insight into the detection and classification capabilities of frequency diverse radar. Performance evaluations and the sort function analysis indicate that the optimal OS range can span from the minimum to the maximum values depending on the statistical distribution of the target and clutter. The OS filter is shown to be a consistent and biased estimator of the quantiles of the received signal distribution. The features of the OS filters and the n-pulse integrator that are critical to detection performance have been compared to determine the proper application of each processor. It has also been shown that detection based on a single OS performs better than the n-pulse integrator when a significant shape difference exists between the target and clutter distributions. Furthermore, a procedure has been developed for the OS filter to determine optimal rank based on the Neyman-Pearson criterion. The results of the the study indicate a relationship between the skewness of the input signal distributions and the optimal rank.

II. RELEVANCE OF WORK TO SDIO GOALS

The project is relevant to the SDIO Program since it deals with potentially superior radar detection techniques. The techniques developed are critical to strategic defense surveillance, target tracking and data acquisition where clutter interference is a primary limiting factor. In addition, since the techniques developed are based on the frequency diversity principles, they are potentially less susceptible to jamming and other countermeasures. Furthermore, the nonlinear processing techniques developed here have other potential military applications in sonar (i.e. submarine detection in sea clutter) and remote optical imaging for target recognition in clutter (i.e. speckle), as well as in civilian applications such as non-destructive testing and medical imaging.

III. SUMMARY OF ACCOMPLISHMENTS

The major highlights and accomplishments of the project are provided below in a summary format. The attached list of articles, which have resulted from this project provide the details of accomplishments.

1) Adaptive Techniques for Determination of Optimal Processing Parameters

The most recent work has focused on the development of techniques which can predict the optimal spectral region for SSP, in particular two techniques have been developed to predict the optimal spectral region for the SSP technique namely, Spectral Histogram and Group Delay Statistics Techniques. The Spectral Histogram Technique determines the frequency with which the spectral windows are selected in the minimization algorithm. Theoretical and experimental results indicate that the most frequently selected windows are also the windows with the highest Signal-to-Noise Ratios (SNR s). Alternately, these results have been examined in further detail to determine the link between the SNR and group delay of a given spectral window and its probability of selection by the minimization algorithm. Similarly, the theoretical and experimental results show that signals with relatively constant group delays have high SNR s, and hence are selected more often by the minimization algorithm. These results have significant ramifications in the adaptive optimimization and real-time application of the frequency diverse algorithms (i.e., SSP Techniques).

An alternative approach has also been developed, which selects the optimal spectral range over which SSP can be performed base on the polarity thresholding (PT) algorithm. This technique weights the processed frequency diverse data by a factor which is inversely proportional to the number of polarity reversals exhibited by the data at each time instant. The weighting can be linear or nonlinear (e.g. exponential) and the proposed technique can be applied to any SSP algorithm, such as minimization, PT, LA, etc. Since the optimal spectral range is likely to vary with the clutter statistics and target characteristics, it is crucial to select the optimal spectral range directly, with no operator interference or use of a trial-and-error approach.

2) Robust Techniques for Target Detection

In this work, a nonlinear operation which calculates the geometric mean was applied to the multiple observation detection problem consisting of frequency diverse data with unknown variances. Theoretical analysis and simulation results show that under these assumptions, the geometric mean algorithm produces higher signal-to-noise ratio enhancement and is more robust with respect to the spectral region selected. Therefore, the geometric mean operation is suitable for the general multiple observation problem with unknown variances and when the optimal spectral region cannot be identified apriori. The geometric mean algorithm has also been examined experimentally using one and two-dimensional ultrasonic data. The experimental results confirm the theoretical analysis and indicate the feasibility of this technique for robust target detection.

3) Non-Parametric Target Detection Techniques

The frequency diversity techniques based on SSP have been shown to be an efficient method for discriminating between target and clutter base on the differences between their rf phase patterns. An alternate approach has been developed based on constant false-alarm thresholds using non-parametric F-test technique applied to the rf SSP vectors. Experimental results indicate the technique is capable of distinguishing between target and clutter regions.

4) Rank Determination for Order Statistic Filters

The minimization algorithm is a special case (i.e., order 1) of the order statistic filters, which can select amplitudes between minimum and maximum for the frequency diverse data ensemble. The statistical characteristics (i.e., SNR s) of the narrowband frequency diverse signals have been analyzed, both theoretically and experimentally to determine the affect of the processing order on the performance SSP output. In general, the best SNR enhancement results will be obtained by selecting the minimum order for the non-target locations, and the maximum order for the target location. However, the same order must be used to process both types data since the target location is unknown apriori. The results of this study show that when all the narrowband signals exhibit sufficiently high SNR, the minimum order will yield the best SNR enhancement. However, as the SNR of the narrowband signals decreases, best results are obtained for lower orders other than the minimum. Hence, the selection of the spectral region for obtaining the frequency diverse signals is the most crucial parameter which affects the performance of the order statistic filters.

5) Order Statistic Characterization and Signal Processing for Nonparametric, Robust and Adaptive Detection Systems

The detection and classification schemes for radar clutter and targets have been investigated. It has been shown that techniques based on Order Statistic (OS) information can characterize amplitude statistics, and also some forms of correlation, over broad variations in the distribution of the received signals. The development of OS characterization and adaptive detection have been examined. The classification schemes with operational simplicity and good performance over a broad range of target and interference properties were emphasized. The fundamental issue of this research involved the determination to what extent OS filters and rank relationships of data can characterize various statistical processes. The results from this information were applied to the design of detectors and classifiers for radar targets and clutter. The median OS has been the major research focus over the last two decades. This research examined the information contribution of all the OS filters ranging from minimum to maximum order. The OS filters were examined to understand how correlation information can be extracted from sets of finite samples and applied in the design of detectors. The idea of using ranked data on the noncoherent and quadrature components of the radar signal is proposed for extracting more detailed correlation and phase information from the target and clutter signals.

The OS characterization offers a novel way to measure and record both amplitude and certain types of correlation statistics and can be implemented in real-time. Critical research issues are

improving the efficiency of extracting and storing OS data in real-time systems. The parallel structure for processing OS data suggests that simple and fast processors can be designed and implemented in real-time. The relationship between the degree of correlation between samples and the accuracy in estimating the underlying distribution have been examined. In this study, two design approaches will be pursued based on Order Statistics (OS) processors. One design approach utilizes Linearly Combined Order Statistics (LCOS) towards CFAR detection for Rayleigh Clutter. The other design approach focuses on the OS characterization in a multisensor environment for Weibull clutter with varying skewness. OS characterization allows for parallel computations and enables the detector to track or censor changes in the clutter statistics.

In most recent work, Linearly Combined Order Statistics (LCOS) CFAR detectors were examined for efficient and robust threshold estimation resulting in improved target detection. The optimization of target detection entails the utilization of an efficient scale parameter estimate for the threshold corresponding to the Censored Maximum Likelihood (CML) and Best Linear Unbiased (BLU) estimators. The design of these CFAR detectors and the probability of detection performance under Lehmann's alternative hypothesis are mathematically analyzed when the back-ground observations have homogeneous and heterogeneous distributions. It is shown that improvements in terms of CFAR loss can be made from utilizing these techniques. The second approach examines the error associated with the CFAR design for local decisions at each OS detector assuming a piece-wise linear characterization of the clutter density function. This model has the ability to adapt to changes in the skewness of clutter distribution. Parameters of this model are estimated using local statistics of the clutter. Several cases of skewness were tested and compared to those made by the CFAR detector assuming exponentially distributed observations. It has been found that the OS characterization can maintain the probability of false alarm in nonstationary Weibull clutter environments. Results demonstrate the superior performance of the novel algorithms introduced, and indicate their feasibility in radar detection, thus, warranting further investigation for generalized target and clutter distributions.

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